Improving the energy system for a rural community in developing countries

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General Introduction

Chapter 1
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1.1 Energy access situation in developing countries

Access to modern energy services is vital for societal wellbeing and countries' economic development. A modern energy system in tropical developing countries includes having reliable and affordable access to an improved cooking facility and having a connection to electricity [1, 2]. However, by the year 2009, about 2.6 billion people worldwide relied on biomass energy for cooking and 1.3 billion did not have a connection to electricity[1]. By the year 2030, the number of people without access to improved cooking technology will be increased to about 2.7 billion and about 1 billion people will remain without electricity. The additional number of people without access to improved cooking technology relates to the increasing population. About 45% of the people deprived of access to a clean cooking facility live in Sub-Saharan Africa. Moreover, by the year 2030 about 70% and 50% of the people in this region will remain dependent on traditional biomass energy and without electricity respectively. A recent report of the International Energy Agency (IEA) shows similar evidence[3]. Accordingly, the regional and rural electricity coverage remains at 32% and 20% compared to the world average coverage of 83% and 70% respectively. The number of people relying on traditional use of biomass energy increased by 15% in 2013 compared to the data in the 2009 report[1, 3]. About 50% of the people without access to a clean cooking facility and electricity in Sub-Saharan Africa live in Nigeria, Ethiopia, Democratic republic of Congo, Tanzania and Kenya. The energy access data in these countries are also shown in Fig.1.1.

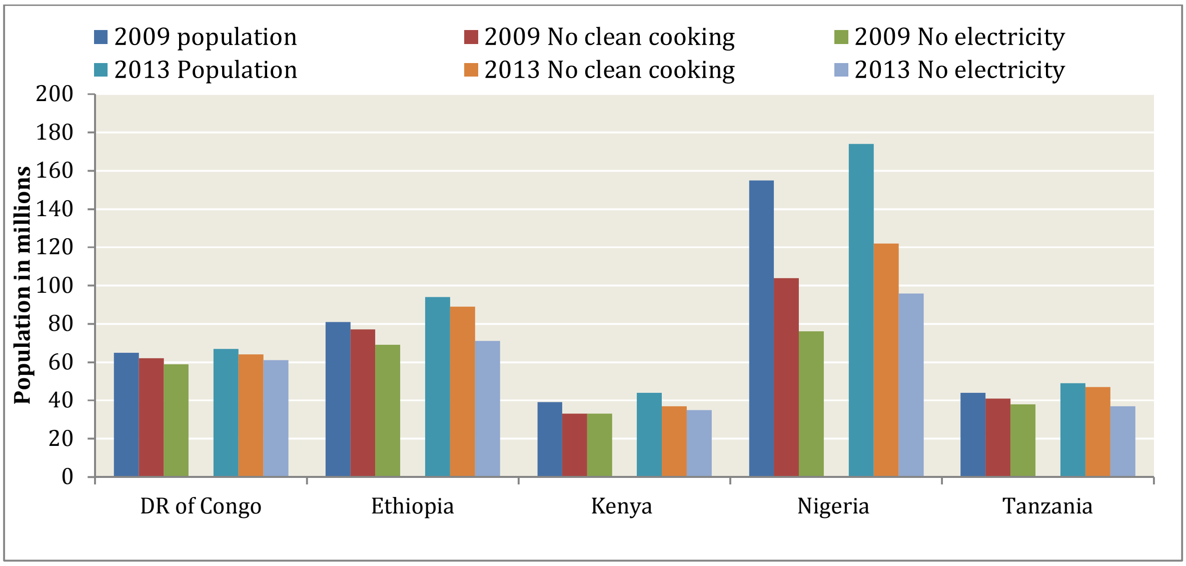

Fig.1.1 The top five Sub-Saharan African countries without access to clean cooking facilities and electricity in the years 2009 and 2013 based on [1, 3]

Lack of access to modern energy services has several socioeconomic and environmental impacts. The most important impacts are decline of common forests, exposure to indoor air pollution and high labor requirements for extraction of firewood. The scale of the impacts depends on the type of fuel sources and technologies used for conversion.

Households frequently cook food with wood obtained from common forests. Common forests are public resources with unrestricted access. In addition, common forests serve as a means of income for poor urban and rural households selling firewood and charcoal. This creates a heavy reliance of the urban population on common resources through rural-urban business[4]. The heavy reliance of rural population for energy and income aggravates the intensity of firewood scarcity and deforestation [4, 5]. In particular, the rate of deforestation is high in countries where large groups in the population depend on biomass energy for cooking. Ethiopia, Nigeria, Pakistan, Sri Lanka and Uganda are among the countries of the world with the highest wood fuel biomass pressure and high rate of deforestation[6]. Moreover, the vast majority of households in rural developing countries use open fire stoves for cooking. Open fire stoves convert only about 10% of the energy content of the biomass [7, 8]. Meeting the cooking energy demand thus requires a large quantity of wood which can have significant effects on the availability of wood. When firewood is scarce households shift to crop residues and dung as a substitute. For instance, in highland areas of Ethiopia where firewood is scarce, dung substitutes about 30% of the firewood demand[9, 10]. Primarily these resources are used as a substitute for inorganic fertilizer and soil mulching[11]. Direct combustion of residues and dung for energy thus affects the availability of nutrients to the soil[10, 12]. Hence, use of common forest firewood and agricultural bio-wastes in a traditional stove would have significant impacts on the availability of biomass and on the environment.

The lack of availability of biomass and its use in inefficient stoves can have many of socio-economic and health consequences. When fuel woods are scarce people will be forced to walk a long distance to where sufficient resources are available. Women and young girls are traditionally in charge of household chores and firewood collection. A comparative overview of daily working hours of men and women in Sub-Saharan Africa is shown in Table 1.1. Women spend 1-2 hours per day to collect firewood at the risk of becoming deprived of education and other more productive activities [13]. Spending more time for energy can compromise the time they require for other activities. As shown in the Table and related literature, women in the region are forced to work more than 12 hours per day, thus more than 50% of them are time-strapped[13-15]. Spending such an amount of time on household chores will have huge impacts on the productive time these people can contribute to the economy of the family. When women are deprived of time, they are less likely able to look after their children, to take care of them and the family. This will have significant effects on the development of the children and their health condition. In addition, combustion of biomass in inefficient stoves produces incomplete combustion byproducts (ICB) which are hazardous to human health. Several studies have shown the cause-effect relationships of traditional use of biomass energy and human health [16-19]. A recent report by World Health Organization (WHO) shows that more than 4 million people die prematurely per year due to illness attributed to the household air pollution caused by inefficient use of solid fuel for cooking[19]. Lack of access to improved energy services also includes energy for lighting. Most rural households use kerosene wick lamps for lighting. They produce many hazardous byproducts like black carbon which can seriously affect human health[20]. Some studies have shown detrimental economic, environmental and health effects of the use of kerosene wick lamps for lighting[20, 21]. Hence, an urgent solution is needed to curb the adverse environmental, socioeconomic and health effects of the traditional use of energy for cooking and lighting.

Table 1.1.Time spent on different activities by men and women (mean hours per day)

	Daily activities	man	woman
1	Care work	0.10	1.0
2	Domestic work	1.5	5.5
3	Firewood and water collection	0.04	1.5
4	Work inside the household (1&2&3)	1.5	8.0
5	Work outside the house	5.0	4.0
	Total work time (4&5)	6.5	12.0

Source: adapted from[13-15]

Many attempts have been made to provide improved energy facilities to households living in rural developing countries. Major progress began during the nineteen seventies and eighties when the relationship between wood-based fuel and deforestation became known [4, 5, 22]. The mitigation efforts made ever since and still ongoing vary across the regions and countries due to differing policies. In principle, providing improved energy facilities requires a lot of investments[1, 23]. In fact, most of the improved energy implementation programs were done centrally as a top-down approach. Such programs usually neglect local practices and user interests. Failing to take public interests into account in these programs strongly affects the implementation and sustainability of the system[24]. Recent literature on the global improved biomass cook stove programs shows the lack of success of most of the top-down approach programs due to their failure to address local interests and culture[25]. Similar constraining factors are observed with the biogas implementation programs[26, 27]. Biogas technology aims to provide a clean and efficient energy for cooking and its slurry for natural fertilizers. India and China are the leading countries by developing cost-effective biogas digesters and dissemination[26]. Many African and other Asian countries also followed their footsteps and developed their biogas programs, but remain now at a standstill, and only a few success stories could be found [27, 28]. As a consequence, only less than one-third of the global population primarily relying on solid fuel uses improved cooking stoves[6]. The problem is worse in rural Sub-Saharan Africa where about 95% of the population still rely on the traditional use of biomass energy. Failing to articulate local interests and conditions affects the progress of modern energy technology adoption, installation and use [24, 25]. Hence, these factors should be understood from the grassroots level before starting any improved rural energy programs.

1.2 Implication of energy demand variation

The household energy demand includes cooking, lighting, heating and appliances. The variation between households energy demand exists in the intensity of the energy and preferences of the technologies providing the services. The variation in the amount of energy for lighting reflects the number of lighting facilities, their efficiency and length of time of use. Hence, households using similar light lamps for the same period consume equal amounts of energy irrespective of their location. The energy demand for electronic appliances in rural developing countries is very small due to lack of high energy demanding appliances. Nevertheless, urban households with a higher income tend to use high energy for appliances. The energy need for heating depends on the geographic condition. However, most households without access to improved energy services are living in tropical climates where the energy for heating is not a big issue. Important demand diversity between western and developing countries as well as between urban and rural households exists in the energy for cooking.

In western and temperate climates, the main share of the household energy demand is for heating and appliances[29]. The cooking energy demand constitutes the smallest share of the demand presumably due to consumption of processed food. Moreover, the energy system is well organized with efficient stoves using high-quality energy from electricity and gas.

In contrast, the demand variation between rural and urban developing countries is complex. In rural areas, the energy demand for cooking is relatively high. Here, people generally consume unprocessed food requiring long cooking hours. In addition, people do not have a facility to store cooked food, thus they cook more frequently. Long cooking hours together with frequent cooking leads to a high cooking energy share of the demand. The cooking energy demand in rural areas accounts for about 90% of the demand[30, 31]. In contrast, the urban households cooking energy demand depends on the socio-economic condition of the households. Urban households are generally connected to the grid which enables them to use electricity for cooking. However, charcoal still remains one of the main energy sources for regular cooking. Poor urban households who are unable to afford electricity mostly rely on biomass energy for all cooking practices[32]. However, it is reported in literature that urban households are more likely willing to shift to a modern energy supply following their increasing income[33]. It is noted that urban households are more accessible to semi-processed food compared to rural households relying on their own produce. Moreover, cooking unprocessed food requires suitable cooking stoves matching local cooking habits. Various studies showed the effect of local energy use conditions, cooking behavior and customs on adoption and sustained use of improved energy technologies [34, 35]. Energy technologies failing to fit local cooking habits and foods are frequently not accepted by users. Thus satisfying the rural developing country's cooking energy demand with western technology appears not to be possible. Hence, energy technologies fitting local food and cooking habits need to be studied taking into account their technical modification with local resources.

1.3 Availability of resources

Provision of improved energy services for rural demand requires the availability of a sufficient amount of resources. Resources can be related to energy sources and labor (time) for their use.

The energy for the demand can be obtained from different sources. In western and oil-rich countries, the demand for household energy is still largely met by fossil fuel sources. However, most countries without access to modern energy systems are net oil importers. Due to growing environmental concerns and rising oil price, fossil fuel sources cannot be a realistic option for them. Yet most of the countries deprived of access to improved energy services have tropical climates presumably with abundant renewable energy resources. However, renewable energy resources are not evenly distributed across the world, regions and countries and within the country itself. Several assessments have indicated the global variation of these resources specially with hydro, wind and solar[36, 37]. Solar, wind and hydro resources are suitable to provide electrical energy for large and small scales. However, the small scale application of hydro and wind depends on their local availability determined by the local geographic and climatic conditions. The effects of these conditions can be small on local solar energy because of the uniformly arriving solar radiation on certain locations. However, their local potential sufficiency for the demand needs to be determined. Otherwise energy from biomass can be used as an alternative.

Biomass energy can be divided into common and produced resources. Common resources are those owned collectively for free access. Availability of these resources depends on the level of exploitation. In most areas, these resources are already over-exploited and scarce. Availability for the demand depends on the time that could be spent on collection and transportation. Spending much time on extraction of resources involves high labor costs and correspondingly less productive time to contribute to household's income.

The availability of produced biomass also relies on the presence of land resources and its yield [38]. The availability and productivity of land varies from place to place and from scale to scale. Hence, an estimate of resources produced ata national or regional level may not reflect equal availability at local and household level. Most assessments made at the national level use average values following a top-down average approach. The top-down approach is essential to show the general overview of the available potential at a large scale. Many studies have reported a large potential of biomass energy resources at global and national scale by using average values [38-40]. Assessments of the potential at the local scale require insight in specific households' resource ownership. However, household resources are usually unevenly distributed. Households holding a large area of land can produce an excess of biomass while those holding a small parcel of land can hardly produce enough. In addition, households can decide on whether to use their bio-wastes for energy supply or for soil mulching and for feed stuff. Hence, an assessment made at household level following a bottom-up approach shows the real potential rather than an assessment made at national scale. Most studies made at national scale usually overlooked household factors and use national average values [41-43]. The potential assessment made at the household level can be vital for the implementation of biomass energy technology that could deliver continuous functionality and sustainability. Hence, the potential at household scales needs to be understood taking into account household ownership and competing purposes.

Household resources include availability of time or labor for processing resources or running the technology. Households living in rural areas of developing countries depend on the seasonal income from subsistent farming. Their income is limited to the crop harvesting season and selling of livestock. Money coming from these sources is expected to cover all household expenses such as clothing etc. The money left after covering all the expenses may not be sufficient to pay for energy or for labor. Most rural households just spend their time to get the energy for their demands. One of the main limitations of dependence on a common resource pool is the requirement for large labor time. Time is equally important for the operation of other biomass energy technologies in particular anaerobic digesters. Biogas production needs daily collection of feedstock, water and removal of slurry. Hence, biogas production with long operation time may not be sustainable due to consumption of high labor. Hence, the time required for the operation of the technology needs to be understood at least relative to the time needed for the traditional energy system.

1.4 Drivers and challenges in addressing the issues

Mankind has gone through several energy transitions in the past five centuries although significant progress is made around the late nineteen fifties[44]. The latter transitions are driven by the invention and development of more fuel types, technological changes and services. These historical transitions are relevant in understanding the perspective of the current energy transition in developing countries. Currently, people have different choices of energy sources and technologies. In particular, the present advanced communication technologies are vital to make people aware of the advantage of modern energy services. The increasing demand for micro-electronic appliances is a good example. A recent estimate shows that more than one in three Africans had at least one mobile subscription and about 76% of the population has Global System for Mobile communication (GSM) coverage while the electrification rate in their countries is still about 30%[3, 45]. According to this estimate, more than 358 million people in Sub-Saharan Africa are covered by mobile networks but they do not have access to an electricity grid. All these technologies require electrical energy for their operation. In addition, improvement in education can be a stimulus to aim for a better life and improved energy access. In many developing countries education is considered as a basic human right where every child should go to school at least for basic education. Studies show that adoption of improved energy technology increases with the level of education and technology penetration[46, 47]. To date, it is not uncommon to find a television set in remote rural areas among households able to afford diesel generators or solar PV. Hence, an increase in demand of micro-electronic appliances and awareness can be big drivers for improved energy technology adoption and use.

An increase in micro-electronic penetration can be an indication of progress of development. Moreover, most of the present technological drivers use electrical energy for their operation. In contrast, the number of people relying on biomass energy for cooking did not decrease but rather increased as shown in Fig.1.1. However, providing access to improved cooking energy technology remains a challenge despite all the emerging drivers. This can be a good indication of focusing policies and other challenging factors related to cooking services. Some studies identified challenging factors attributed to resources, demands, technologies and policies [23, 34]. Currently, most energy policies in developing countries focus on large-scale grid electrification directly contributing to the economy[48, 49]. However, connecting remote households to the grid energy system is inconceivable in the near future. Furthermore, just connecting households to an electricity grid may not solve their cooking energy problems. Energy policy focusing on rural energy transition is needed.

A lot of energy transition policies are proposed at a global scale to transform the traditional energy system to a more efficient energy technology[1, 50]. For a long time the rural household energy transition was explained with the prominent energy ladder model which considers the household socioeconomic situation as the driver of the transition[51, 52].This model has been criticized for its linear transition mode since an increase in household economy does not necessarily achieve a complete transition from traditional to modern [53, 54]. It is obvious that an increase in the income of households helps them to afford the costs of the technology. However, the decision to adopt and use the technology depends on the local conditions. A survey report from different villages in

Mexico affirms that stove types, cooking practices, fuel economy, accessibility conditions and cultural preferences came to be the main household decision tools[53]. This decision also varies between urban and rural households. A higher income is more likely to move urban households to the improved energy technology than rural households[33]. As reported in literature, socio-cultural factors related to the demand and the availability of local resources can be more important than increasing income to achieve the transition in rural areas[34]. This indicates the complex behavior of rural energy transition which money alone cannot solve.

In principle, energy transition involves reducing energy need, using efficient technology and applying less polluting energy sources (trias energetica). The first principle is not applicable in rural areas since most households fulfill only a basic need for cooking that cannot be reduced without affecting their bare existence. Use of efficient technology and available renewable energy are the sole options. Hence, efficient and suitable technology addressing local (rural) energy issues needs to be established based on available local resources. However, there are no comprehensive studies yet focusing on an integrated approach involving resources assessment and technological options matching local demands. To achieve these, the following specific research questions should be addressed using system analysis. Are there sufficient renewable energy resources available for the demand? Are there efficient technologies available to convert renewable resources into suitable type of energy to meet the demand? Are the technologies affordable and do they match local conditions? Are they applicable with low labor requirements? Answering these questions is vital in providing better understanding of rural developing country's energy system from resources, demands and selection of suitable technology perspectives. This understanding is helpful to look into new ways of dealing with rural energy transition.

1.5 Aim and scope of the thesis

This thesis aims to determine the availability of renewable energy resources and efficient technologies suitable for rural developing countries' energy demand using the data in Ethiopia. The data from this country is considered by taking into account the rural energy situation, progress of energy projects and availability of data sources. Renewable energy resources are either unevenly distributed or not sufficiently available everywhere. In this thesis, a study is made on the efficiency and suitability of the technology based on local resources and demand. Households need energy for basic, public and productive services. Basic services include meeting the energy demand for cooking, lighting and small electronic appliances. The productive and public energy services include the energy for business, schools, clinics and street light. Meeting the public and the productive demand with energy obtained from household resources may not be feasible in the rural Ethiopian conditions. This study focuses on the energy needed for basic demands. Adoption and installation of improved energy technology requires certain financial resources. However, rural households depend on subsistent seasonal income which may not be sufficient to afford energy prices and their facility. In addition, the financial issues of rural developing countries for improved energy technology adoption are well reported in the literature[1, 23]. Hence, economic aspects of the households and the technology are outside the scope of this thesis. The analyses are made at national, village and household levels by using available national data sources and literature. The thesis contains six chapters including introduction and discussion parts.

The next chapters are organized as follows. **Chapter 2** performs assessments of naturally existing renewable energy resources for different energy applications. The study is made on the assessments of solar, hydro and wind energy for their large scale grid and standalone application and suitability to rural energy system. The analysis made in **chapter 3** focuses on the availability of bio-wastes for the cooking demand at household level. The assessments are made based on the households' resource ownership and competing purposes following a bottom-up approach. **Chapter 4** analyzes the availability of resources and the suitability of the technologies at the village scale. **Chapter 5**analyzes the labor requirements of different biogas energy production systems based on the time spent on resource collection and transportation. The last **Chapter** integrates and discusses the findings in the preceding chapters and presents a concluding summary.